Light Gluino, Light Bottom Squark Scenario, and LEP Predictions

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The scenario of light gluinos and light sbottoms was advocated to explain the discrepancy between the measured and theoretical production of b quarks at the Tevatron. This scenario will have model-independent predictions for $Z \to q\bar{q}\tilde{g}\tilde{g}$ at the Z^0 pole, and $e^+e^- \to q\bar{q}\tilde{g}\tilde{g}$ at LEPII. We show that the data for $Z \to q\bar{q}g^* \to q\bar{q}b\bar{b}$ at LEPI cannot constrain the scenario, because the ratio $\Gamma(Z \to q\bar{q}\tilde{g}\tilde{g})/\Gamma(Z \to q\bar{q}g^* \to q\bar{q}b\bar{b}) = 0.15$–$0.04$ for $m_{\tilde{g}} = 12$–16 GeV is smaller than the uncertainty of the data. However, at LEPII the ratio $\sigma(e^+e^- \to q\bar{q}\tilde{g}\tilde{g})/\sigma(e^+e^- \to q\bar{q}g^* \to q\bar{q}b\bar{b}) \simeq 0.4$–$0.2$ for $m_{\tilde{g}} = 12$–16 GeV, which may give an observable excess in $q\bar{q}b\bar{b}$ events; especially, the $4b$ events.

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Weak-scale supersymmetry is the leading candidate for physics beyond the standard model (SM). Supersymmetry (SUSY) is built on a solid theoretical and mathematical foundation. It is also well motivated as an elegant solution to the gauge hierarchy problem and has merits of gauge-coupling unification, dynamical electroweak-symmetry breaking, and providing a legitimate candidate for dark matter. The search for SUSY will be a major goal of future collider experiments, and in precision measurements, such as $g - 2$ and electric dipole moments [1].

One of the long-standing problems in heavy flavors is the excess in hadronic production of b quarks recorded by both Collider Detector at Fermilab (CDF) and D0 Collaborations [2]. The data are about a factor of 2 larger than the prediction by the most optimal choice of parameters in perturbative QCD (here optimal means that the parameters such as b-quark mass m_b, the factorization scale μ have been tuned to maximize the prediction) [3]. Such a discrepancy was recently interpreted by Berger *et al.* [6] in the scenario of light gluinos and light sbottoms. Light gluinos of mass between 12–16 GeV are pair produced by $q\bar{q}$ and gg fusion processes. These are QCD processes and the cross sections are similar to b-quark production. The gluinos undergo subsequent decays $\tilde{g} \to b\tilde{b}_1^* / \bar{b}\tilde{b}_1$, where the sbottom has a mass 2–5.5 GeV. Therefore, in the final state there are $b\bar{b} + \tilde{b}_1\tilde{b}_1^*$, in which the sbottom either remains stable or decays into other light hadrons (e.g., via R-parity violating couplings) and goes into the b jet. Thus, gluino-pair production gives rise to inclusive b-quark cross section. The mass ranges are chosen so as to reproduce both the total cross section and the transverse momentum spectrum of the b quark. Before Berger *et al.*'s work, there have been some studies in the light sbottom and/or light-gluino scenario [7]. However, such a scenario cannot be ruled out, unless there exists a sneutrino of at most 1–2 GeV.

A light gluino can be established in some moduli-dominated SUSY-breaking models, and can even be the LSP [8]. The gluino-LSP scenario was studied in Ref. [9] (the gluino-NLSP scenario was studied in Ref. [10].) The light gluino scenario is consistent with cosmological constraints and does not affect the precision data as long as the squarks are heavy. However, the implication would be very different if both the gluino and sbottom are light. Therefore, the first impression to Berger *et al.*'s scenario would be that the scenario easily contradicts other experiments, especially the Z^0-pole data because of the light sbottom, as well as the collider search for light gluinos.

Berger *et al.* [6] can defend their scenario by arguing that (i) all previous light gluino limits are not applicable because either the mass range is different or the decay channel of the gluino is different, and (ii) the mixing angle of $\tilde{b}_L$ and $\tilde{b}_R$ can be tuned to a value such that the tree-level coupling of $\tilde{b}_1$ to Z is negligible so as not to upset the Z observables. However, Cao *et al.* [11] showed that such a light gluino and a light sbottom will contribute significantly to R_b via one-loop gluino-sbottom diagrams. In order to suppress such contributions, the second $\tilde{b}_2$ has to be lighter than about 125 GeV (at 2σ level) in order to cancel the contribution of $\tilde{b}_1$ in the gluino-sbottom loop. Cho [12] extended the analysis to the whole set of electroweak precision data and took into account the stop contributions because of the $SU(2)_L$ symmetry. He found a similar conclusion that the $\tilde{b}_2$ must be lighter than about 180 GeV at 5σ level and the left-right mixing of the stop must be sufficiently large. On the other hand, Baek [13] showed that such constraints can be relaxed if CP-violating phases are allowed in the model.

The light gluino and light sbottom scenario will certainly give rise to other interesting signals, e.g., decay of χ_b into the light sbottom [14], enhancement of $t\bar{t}b\bar{b}$ production at hadron colliders [15], decay of Υ into a pair of light sbottoms [16], and flavor-changing effects in radiative decays of B mesons [17]. As mentioned by Berger *et al.*, [6], a light gluino analysis was done by Baer, Cheung, and Gunion [9], in which the gluino is assumed the LSP. Here in this work we modify the analysis by letting the light gluino decay into b and $\tilde{b}_1$, and study the possible constraint and implication at LEP.

In this Letter, we calculate the associated production of a gluino pair with a $q\bar{q}$ pair and compare to the SM prediction of $q\bar{q}b\bar{b}$ at both LEPI and LEPII (here q refers to the sum over u, d, s, c, b and we use the massless quark approximation). We show that the current data from LEPI are not precise enough to constrain Berger *et al.*'s scenario. On the other hand, at LEPII ($\sqrt{s} = 189$–209 GeV) the $q\bar{q}\tilde{g}\tilde{g}$ production cross section is about 40%–20% of the SM production of $q\bar{q}b\bar{b}$, which may be large enough to produce an observable excess in $q\bar{q}b\bar{b}$ events. Similar conclusions can also be drawn on the $4b$ production. Such results are model independent. If Berger *et al.*'s scenario is correct, the above prediction is unavoidable. We, therefore, urge our experimental colleagues at LEP to analyze the $q\bar{q}b\bar{b}$ and $4b$ channels.

At the Z^0 pole, the lowest-order model-independent channel to produce a gluino pair is via a gluon splitting coming off a quark or antiquark, as shown in Fig. 1(a). It is followed by the subsequent decay of gluino $\tilde{g} \to b\tilde{b}_1^*/\bar{b}\tilde{b}_1$, and therefore, it will give rise to $q\bar{q}b\bar{b}$ production. The LEP Collaborations had measured a gluon-splitting process $Z \to q\bar{q}g^* \to q\bar{q}b\bar{b}$ at the Z^0 pole [18–20]. The data are given as

$$\frac{\Gamma(Z \to q\bar{q}g^* \to q\bar{q}b\bar{b})}{\Gamma(Z \to \ \text{hadrons})} = \begin{cases} (2.77 \pm 0.42 \pm 0.57) \times 10^{-3} & \text{ALEPH,} \\ (3.07 \pm 0.53 \pm 0.97) \times 10^{-3} & \text{OPAL,} \\ (3.3 \pm 1.0 \pm 0.8) \times 10^{-3} & \text{DELPHI I,} \\ (2.1 \pm 1.1 \pm 0.9) \times 10^{-3} & \text{DELPHI II.} \end{cases}$$

The above data have been corrected for acceptance and cut efficiencies by each experiment. We combine the above data assuming that the errors are Gaussian, each data has equal weight, and the data are uncorrelated. We obtain the average and the 1σ error as

$$\frac{\Gamma(Z \to q\bar{q}g^* \to q\bar{q}b\bar{b})}{\Gamma(Z \to \ \text{hadrons})} = (2.83 \pm 0.51) \times 10^{-3} . \quad (1)$$

The Feynman diagrams that contribute to the gluon-splitting production of $Z \to q\bar{q}g^* \to q\bar{q}b\bar{b}$ are shown in Fig. 1(b). The Feynman diagrams in Fig. 1(c) contribute to the same final state but can be easily separated from those in Fig. 1(b) by an invariant mass cut on $m_{q\bar{q}}$. In the calculation, we have chosen $m_b = 4.25$ GeV and the strong running coupling is evaluated at $Q^2 = m^2_{b\bar{b}}$, which is the offshellness in the virtual gluon. We obtain in the SM

$$\left.\frac{\Gamma(Z \to q\bar{q}g^* \to q\bar{q}b\bar{b})}{\Gamma(Z \to \ \text{hadrons})}\right|_{\text{SM}} = 2.81 \times 10^{-3} , \quad (2)$$

where we take the total hadronic width of the Z, $\Gamma_{\text{had}} = 1.745$ GeV [21]. It agrees well with the data in Eq. (1).

Now we proceed to calculate $Z \to q\bar{q}\tilde{g}\tilde{g}$ to see if it would contribute at a level larger than the uncertainty of the data. However, we found that

$$\frac{\Gamma(Z \to q\bar{q}\tilde{g}\tilde{g})}{\Gamma(Z \to \ \text{hadrons})} = (0.43\text{–}0.12) \times 10^{-3} \quad (3)$$

for $m_{\tilde{g}} = 12$–16 GeV. We have chosen $\alpha_s(Q^2 = m^2_{\tilde{g}\tilde{g}})$ analogous to the $b\bar{b}$ calculation above. It implies that $\Gamma(Z \to q\bar{q}\tilde{g}\tilde{g})$ is only a small fraction (15% – 4% for $m_{\tilde{g}} = 12$–16 GeV) of $\Gamma(Z \to q\bar{q}g^* \to q\bar{q}b\bar{b})$, plus it is less than the 1σ uncertainty. We conclude that the present LEPI data cannot constrain the scenario. This gluino-pair production is independent of any mixing parameters.

The DELPHI Collaboration [20] also measured the $4b$ production due to the gluon slitting. The statistics is even lower. We would expect $Z \to b\bar{b}\tilde{g}\tilde{g}$ to be subdominant, very similar to the $q\bar{q}\tilde{g}\tilde{g}$ case. We do not pursue it further.

At LEPII, the situation would be different because of higher energies and more phase space. We show the cross section of $\sigma(e^+e^- \to q\bar{q}\tilde{g}\tilde{g})$ versus $m_{\tilde{g}} = 10$–20 GeV for $\sqrt{s} = 189, 209$ GeV in Fig. 2(a). In general, there are two factors affecting the cross section: (i) this is a s-channel process as far as the initial e^+e^- is concerned, and so the

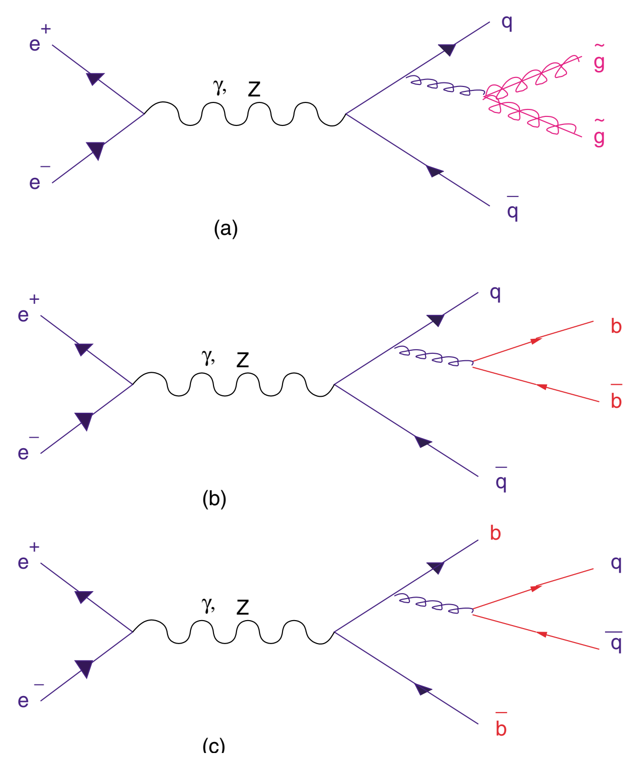

FIG. 1 (color online). Feynman diagrams contributing to (a) $e^+e^-(Z) \to q\bar{q}\tilde{g}\tilde{g}$, (b) $e^+e^-(Z) \to q\bar{q}g^* \to q\bar{q}b\bar{b}$, and (c) $e^+e^-(Z) \to b\bar{b}g^* \to b\bar{b}q\bar{q}$. The diagrams with the gluon bremsstrahlung off the $\bar{q}$ are not shown.

cross section decreases with $\sqrt{s}$, and (ii) as $\sqrt{s}$ increases more phase space is available for the massive gluinos. The cross sections for $\sigma(e^+e^- \to q\bar{q}g^* \to q\bar{q}b\bar{b})$ with $m_b = 4.25$ GeV are 0.19 and 0.17 pb at $\sqrt{s} = 189$ and 209 GeV, respectively. In Fig. 2(b), we plot the ratio

$$R_{\tilde{g}} \equiv \frac{\sigma(e^+e^- \to q\bar{q}\tilde{g}\tilde{g})}{\sigma(e^+e^- \to q\bar{q}g^* \to q\bar{q}b\bar{b})}$$

for $m_{\tilde{g}} = 10$–20 GeV. For the mass range of interest, $m_{\tilde{g}} = 12$–16 GeV, the ratio at $\sqrt{s} = 189\,(209)$ GeV is

$$R_{\tilde{g}} = \begin{cases} 0.38\,(0.41) & \text{for } m_{\tilde{g}} = 12 \text{ GeV}, \\ 0.26\,(0.28) & \text{for } m_{\tilde{g}} = 14 \text{ GeV}, \\ 0.18\,(0.20) & \text{for } m_{\tilde{g}} = 16 \text{ GeV}. \end{cases} \quad (4)$$

Since the rate for gluino-pair production is about 40%–20% of the SM prediction, we would expect an observable excess in $q\bar{q}b\bar{b}$ events at LEPII. We note that the ratio for $\sigma(e^+e^- \to b\bar{b}\tilde{g}\tilde{g})/\sigma(e^+e^- \to b\bar{b}g^* \to b\bar{b}b\bar{b})$ is very similar. Though the $4b$ final state would be more spectacular, the statistics would be a few times lower.

In Fig. 3, we show the angular separation among the final state particles. The decay products of each gluino, i.e., a b quark and a sbottom, are very close to each other with $\cos\theta$ peak at above 0.9. Experimentally it may be very difficult to separate them. Thus, the sbottom will simply go almost along with the b quark. The final state then looks like a $q\bar{q}b\bar{b}$. In Fig. 3, we also show the cosine of the opening angle between the $q\bar{q}$ pair, between the gluino pair before they decay, and between the b quarks decaying from the gluinos. The $q\bar{q}$ pair is back-to-back while the b quarks are very close to each other. In addition, the q and $\bar{q}$ are very energetic while the two b's are soft. This event topology is very similar to that of the SM gluon-splitting process. Thus, we expect the selection efficiencies of the SM gluon-splitting process and the gluino-pair production are very similar.

So far, throughout the analysis we used a value $m_b = 4.25$ GeV, somewhat lower than the value employed in Refs. [2,6]. The main reason is to make the SM prediction in Eq. (2) close enough to the Z^0-pole data in Eq. (1). If we used $m_b = 4.75$ GeV, the SM prediction would be lower but still within 1.2σ of the data in Eq. (1). Therefore, the data in Eq. (1) could not indicate any excess at a significant level. On the other hand, if we change $m_b = 4.75$ GeV in the LEPII calculation, the results change slightly, giving a slightly larger ratio $R_{\tilde{g}}$ of Eq. (4):

$$R_{\tilde{g}} = \begin{cases} 0.45\,(0.49), & \text{for } m_{\tilde{g}} = 12 \text{ GeV}, \\ 0.31\,(0.34), & \text{for } m_{\tilde{g}} = 14 \text{ GeV}, \\ 0.21\,(0.24), & \text{for } m_{\tilde{g}} = 16 \text{ GeV}, \end{cases} \quad (5)$$

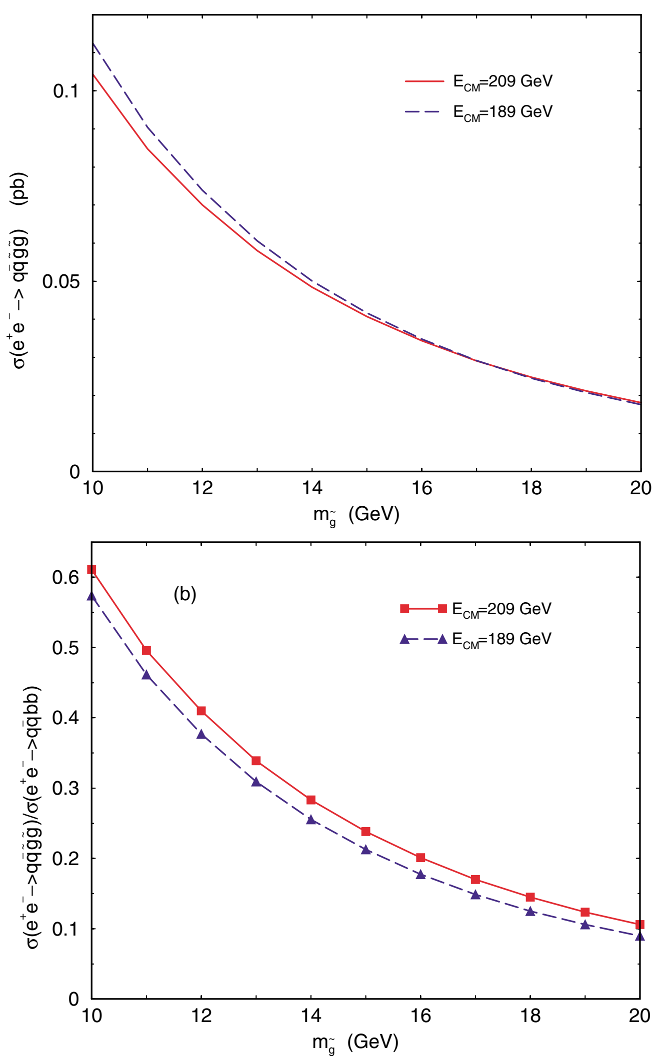

FIG. 2 (color online). (a) The cross section of $\sigma(e^+e^- \to q\bar{q}\tilde{g}\tilde{g})$ versus the gluino mass at $\sqrt{s} = 189, 209$ GeV. (b) The ratio $R_{\tilde{g}}$ versus $m_{\tilde{g}}$ for $\sqrt{s} = 189, 209$ GeV.

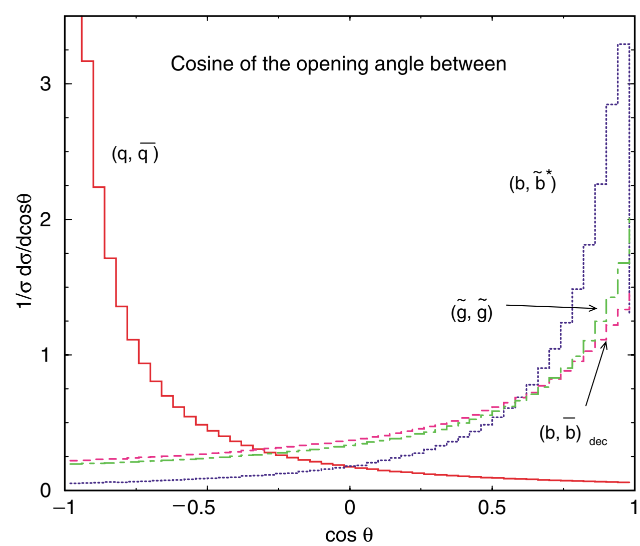

FIG. 3 (color online). Distributions of the cosine of the opening angle between the $q\bar{q}$ pair, between the decay products, a b quark and a sbottom from a gluino, between the gluino pair before they decay, and between the two b quarks from the gluino decay, at $\sqrt{s} = 189$ GeV for $m_{\tilde{g}} = 12$ GeV.

at $\sqrt{s} = 189\,(209)$ GeV for $m_b = 4.75$ GeV. The observability of excess in $q\bar{q}b\bar{b}$ events increases. The result in Eq. (4) would then be more conservative.

There is another process similar to the one shown in Fig. 1(b) with $q, \bar{q}$ replaced by $\tilde{b}_1, \tilde{b}_1^*$. However, $\tilde{b}_1$ couples to the photon with an electric charge $-1/3$ but not to the Z in Berger *et al.*'s scenario. Furthermore, it is a scalar. We, therefore, expect this process to be subdominant to the one that we are considering here. Nevertheless, it gives an additional, yet small, contribution to the excess in $q\bar{q}b\bar{b}$ events.

The effect of including the light gluino and sbottom into the running of the strong coupling constant is rather mild [22]. The difference in α_s is only 6% (3%) when we run the scale down from M_Z to 24 GeV ($M_Z/2$). Thus, this will not affect our result significantly.

Each LEP experiment recorded more than $600\,\mathrm{pb}^{-1}$ luminosity for energy between 183 and 209 GeV, with most luminosity at 189 and 207 GeV [21]. With a total luminosity more than $2\,\mathrm{fb}^{-1}$ collected by four experiments, there should be a sufficient number of $q\bar{q}\tilde{g}\tilde{g}$ signal events above the gluon-splitting background. However, at energies above $2M_W$ other backgrounds such as $WW, ZZ \to 4$ jets have to be discriminated also. Since the $q\bar{q}$ pair is back-to-back and energetic while the $\tilde{g}\tilde{g}$ or $b\bar{b}$ pair tends to be soft and become rather close together, one can make use of this event topology to discriminate the signal from the 4-jet events of WW or ZZ decays. Contamination from gluon splitting into other light quarks can be reduced by displaced vertices. Detailed detector-dependent analysis is beyond the scope of the present paper.

After selective cuts to reduce backgrounds, the number of gluon-splitting $e^+e^- \to q\bar{q}g^* \to q\bar{q}b\bar{b}$ events can be counted. If an excess in such events is observed, it may be due to gluino-pair production followed by the gluino decay $\tilde{g} \to b\tilde{b}_1^*/\bar{b}\tilde{b}_1$ that is discussed in the present paper [23]. Such a scenario of light gluinos and light sbottoms is advocated by Berger *et al.* to explain the excess in b-quark production at the Tevatron. In Fig. 2 and in Eq. (4), we have shown that the gluino-pair production is a significant fraction of the production of $q\bar{q}b\bar{b}$ by gluon splitting. In principle, it should be observed if the light gluino and light sbottom scenario is correct. This prediction is independent of the light sbottom coupling to Z boson, the mass of the second $\tilde{b}_2$, or the $\tilde{b}_L$–$\tilde{b}_R$ mixing angle.

In this Letter, we have calculated the associated production of a gluino pair with a $q\bar{q}$ pair and compared to the SM prediction of $q\bar{q}b\bar{b}$ at both LEPI and LEPII. We have shown that the current data from LEPI are not precise enough to constrain Berger *et al.*'s scenario. On the other hand, at LEPII the $q\bar{q}\tilde{g}\tilde{g}$ production is about 40%–20% of the SM production of $q\bar{q}b\bar{b}$ by gluon splitting, which may be large enough to produce an observable excess in $q\bar{q}b\bar{b}$ events. A similar conclusion can also be drawn on the $4b$ production. If Berger *et al.*'s scenario is correct, the prediction here is unavoidable. We, therefore, urge our experimental colleagues at LEP to analyze the gluon-splitting $q\bar{q}b\bar{b}$ and $4b$ events. Wishfully, this is a sign of supersymmetry.

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